

# Sensitivity of atmospheric neutrino experiments to neutrino non-standard interactions

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**Abstract.** We study the sensitivity of atmospheric neutrino experiments to the neutrino non-standard interactions (NSI) which is motivated by the tension between the two mass squared differences extracted from the KamLAND and solar neutrino experiments. In this study the sensitivity of the future Hyper-Kamiokande experiments for 4438 days to NSI is shown. Assuming that the mass hierarchy is known, we find that the best-fit value from the solar neutrino and KamLAND data can be tested at more than  $8\sigma$ , while the one from the global analysis can be examined at  $5.0\sigma$  ( $1.4\sigma$ ) for the normal (inverted) mass hierarchy.

## 1. Introduction

It is well established by solar, atmospheric, reactor and accelerator neutrino experiments that neutrinos have masses and mixings. In the standard three flavor neutrino oscillation framework, there are three mixing angles  $\theta_{12}$ ,  $\theta_{13}$ ,  $\theta_{23}$  and two mass-squared differences  $\Delta m_{31}^2$ ,  $\Delta m_{21}^2$ . However we do not know the value of the Dirac CP phase  $\delta_{\text{CP}}$ , the sign of  $\Delta m_{31}^2$  (the mass hierarchy) and the octant of  $\theta_{23}$  (the sign of  $\pi/4 - \theta_{23}$ ).

We are entering the era of high precision neutrino oscillation measurements to measure the unknown parameters mentioned above. Recently, it was pointed out that there is a tension in which smaller mass squared differences  $\Delta m_{21}^2$  extracted from the global fit of the solar neutrinos are  $2\sigma$  smaller than that from the KamLAND experiment. The tension between KamLAND and solar neutrinos can be solved by flavor-dependent nonstandard interactions (NSI). Such a hint for NSI gives us a strong motivation to study NSI in propagation in details.

In Ref. [4] it was shown that the atmospheric neutrino measurements at Hyper-Kamiokande has a very good sensitivity to the NSI. In this paper we discuss the sensitivity of the atmospheric neutrino measurements at Hyper-Kamiokande to NSI with a parametrization which is used in Ref. [3]. The parametrization used in Ref. [3] is different from the ordinary one used in Ref. [4]. Therefore a non-trivial mapping is required to compare the results in these two parametrization. Our analysis was performed by taking this non-trivial mapping into account.

## 2. The sensitivity of Hyper-Kamiokande to NSI

In the three flavor neutrino oscillation framework with NSI, the neutrino evolution is governed by the Dirac equation:

$$i \frac{d}{dx} \begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix} = \left[ U \text{diag}(0, \Delta E_{21}, \Delta E_{31}) U^{-1} + \mathcal{A} \right] \begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix}, \quad (1)$$

where  $\Delta E_{jk} \equiv \Delta m_{jk}^2/2E \equiv (m_j^2 - m_k^2)/2E$ ,  $c_{jk} \equiv \cos \theta_{jk}$ ,  $s_{jk} \equiv \sin \theta_{jk}$ ,  $U$  stands for the leptonic mixing matrix and  $\mathcal{A}$  stands for the matter potential with NSI expressed as

$$\mathcal{A} \equiv \sqrt{2}G_F N_e \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}. \quad (2)$$

In the investigation of the sensitivity of solar neutrinos to NSI [3], a NSI parametrization  $(\epsilon_D^f, \epsilon_N^f)$  which is different from that in equation (2) was introduced. One can find the definition of  $(\epsilon_D^f, \epsilon_N^f)$  in Ref. [3]. Notice that the fermion subscript  $f$  is not important in the case of atmospheric neutrinos with one particular choice of  $f = u$  or  $f = d$  at a time because the number densities of up and down quarks are approximately the same in the Earth.

We concentrate on only one particular choice of  $f = d$  in this paper and therefore we omit the fermion subscript  $f$  in our analysis.

Our aim is to investigate the sensitivity of the atmospheric neutrino experiment to NSI which is parametrized as  $(\epsilon_D, \epsilon_N)$  and this is done as follows.

- (i) Set a grid on the  $(\epsilon_D, |\epsilon_N|)$  plane.
- (ii) Get a parameter set  $\epsilon_{\alpha\beta}$  taking non-trivial mapping [5] into account for the given point  $(\epsilon_D, |\epsilon_N|)$  on the grid.
- (iii) Dismiss the parameter set if it is obviously excluded by the previous studies [1, 2, 4].
- (iv) Calculate  $\chi^2$  for each parameter set which passed the test (iii) and then obtain the minimum value of  $\chi^2$  for the given  $(\epsilon_D, |\epsilon_N|)$ .

The results are shown in figure.1. The best fit values  $(\epsilon_D^d, \epsilon_N^d) = (-0.12, -0.16)$  for NSI with  $f = d$  from the solar neutrino and KamLAND data given by Ref. [3] is excluded at  $11\sigma$  ( $8.2\sigma$ ) for the normal (inverted) hierarchy. In the case of NSI with  $f = u$ , the best fit value  $(\epsilon_D^u, \epsilon_N^u) = (-0.22, -0.30)$  is far from the standard scenario  $(\epsilon_D, \epsilon_N) = (0.0, 0.0)$  compared with the case of  $f = u$  and also excluded at  $38\sigma$  ( $35\sigma$ ) for the normal (inverted) hierarchy. On the other hand, the best fit value from the global analysis of the neutrino oscillation data [3]  $(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$  for NSI with  $f = d$  is excluded at  $5.0\sigma$  ( $3.7\sigma$ ) for the normal (inverted) hierarchy. In the case of NSI with  $f = u$ , the best fit value  $(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$  is excluded at  $5.0\sigma$  ( $1.4\sigma$ ) for the normal (inverted) hierarchy.

To see which bin contributes to  $\chi^2$  most, we focused on the difference between the number of events of the standard scenario and that of the scenario with NSI (the red and black circle points in figure 1). Then we found that the multi-GeV  $\mu$ -like events coming from the below in the high-energy-bin contributes most to  $\chi^2$ . This is because difference between the oscillation probability with NSI and without NSI is large where the neutrino energy is above 10 GeV. We plotted the numbers of events for the multi-GeV  $\mu$ -like events in the high-energy-bin in figure 2.

### 3. Conclusion

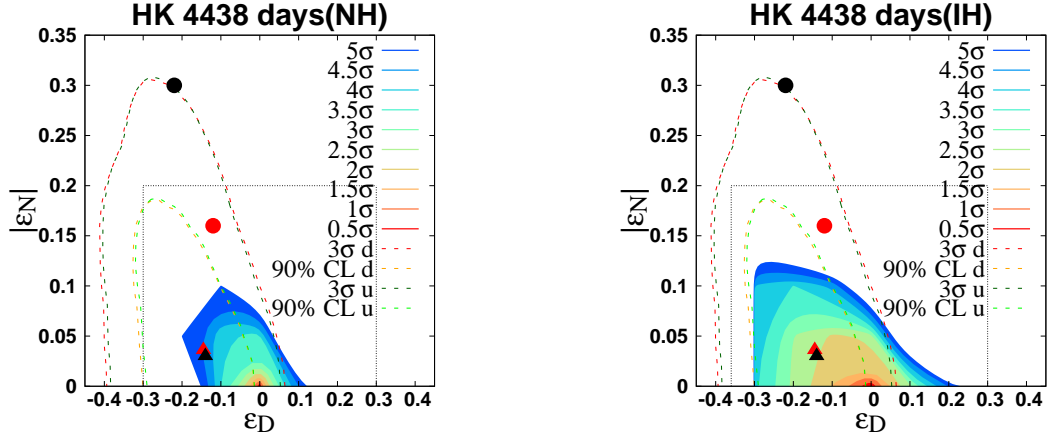
In this paper we have studied the sensitivity of the future HK atmospheric neutrino experiment to NSI which is suggested by the tension between the mass squared differences from the solar neutrino and KamLAND data. We find that the best-fit value from the solar neutrino and KamLAND data can be tested at more than  $8\sigma$ , while the one from the global analysis can be examined at  $5.0\sigma$  ( $1.4\sigma$ ) for the normal (inverted) mass hierarchy. It is worth noting that the scenario with NSI can be tested by looking at the multi-GeV  $\mu$ -like events in the future atmospheric neutrino experiments with high precision measurements.

### Acknowledgments

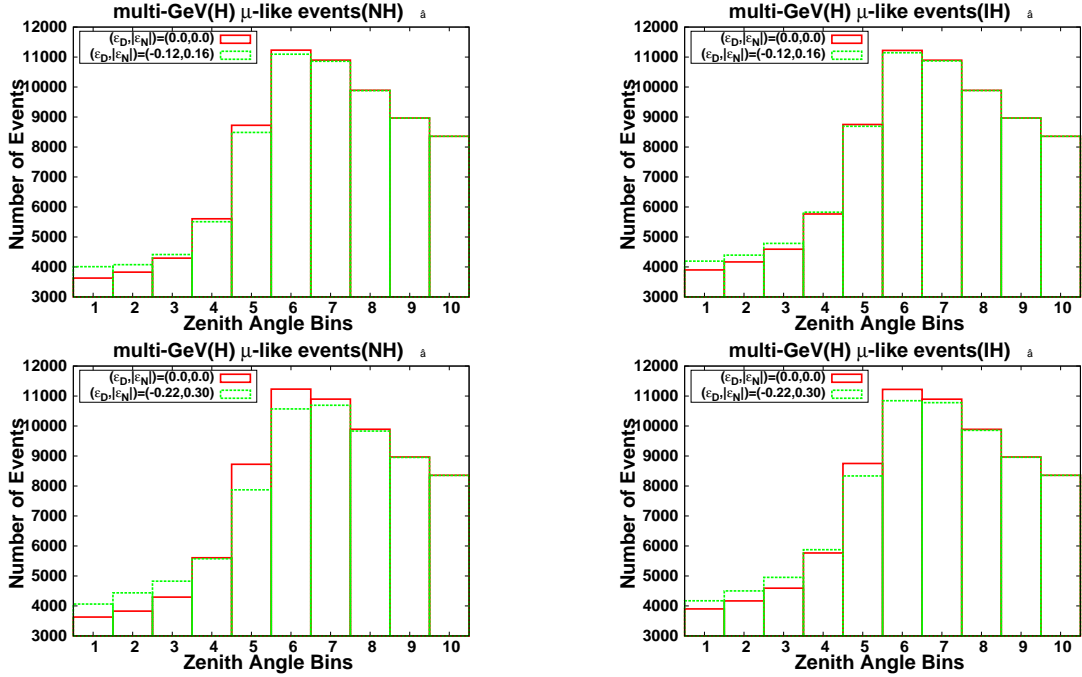
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**Figure 1.** The allowed region in the  $(\epsilon_D, |\epsilon_N|)$ . We calculated  $\chi^2$  within the area surrounded by dotted lines and at the best fit points. The triangles and circles are the best-fit values given by Ref. [3]. The dashed lines are the boundaries of the allowed regions from the global neutrino oscillation experiments analysis.



**Figure 2.** The number of the high-energy-bin multi-GeV  $\mu$ -like events (red and green boxes are the standard scenario and the scenario with NSI, respectively). The horizontal axis is the zenith angle bin(1 for  $-1.0 < \cos \Theta < -0.8$ , ..., 10 for  $0.8 < \cos \Theta < 1.0$  ).